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# Development of a New Nondestructive Inspection Strategy for Corroded Multistrand Anchor Cables

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**INTRODUCTION AND BACKGROUND:** This Coastal and Hydraulics Technical Note (CHETN) describes recent efforts undertaken to develop a nondestructive test (NDT) method to detect and locate broken in situ wires within seven-strand post-tension cables used in multistrand anchor systems. While broken wire detection is pursued here as an easier first step, characterization of cross-sectional losses within a cable due to corrosion is the ultimate goal of the cable NDT research. This need was described in the initial project publication Technical Note ERDC\CHL CHETN-IX-28 (Ebeling et al. 2012) and is part of a broader research effort under the work unit Probabilistic Assessment of the Reduced Capacity of Multistrand Post Tensioned Ground Anchorage due to Tendon Corrosion. Highlights from the NDT research component of that effort are briefly introduced in the "INITIAL GUIDED WAVE INVESTIGATIONS" section of this technical note; additional findings and background information are presented in reports by Ebeling et al. (2013) and Haskins et al. (2014).

Cable post-tensioning is a method of strengthening concrete with high-strength steel strands. These are typically referred to as tendons and are commonly used in dams, bridges, stadiums, parking structures, rock and soil anchors, houses, and many other structures. Figure 1 (left) and (middle) show a typical cable and multistrand anchor head. While corrosion protection mechanisms have improved over the years, a large inventory of cables with poor or marginal corrosion protection will remain in service for years to come. Even with a modern corrosion protection mechanism, there is a potential for corrosion in the stress-concentrated region of the grip wedge where the assemblage is in closest proximity to the environment and the jacketing materials must be cut back for the wedge-to-steel compression mechanism to function.

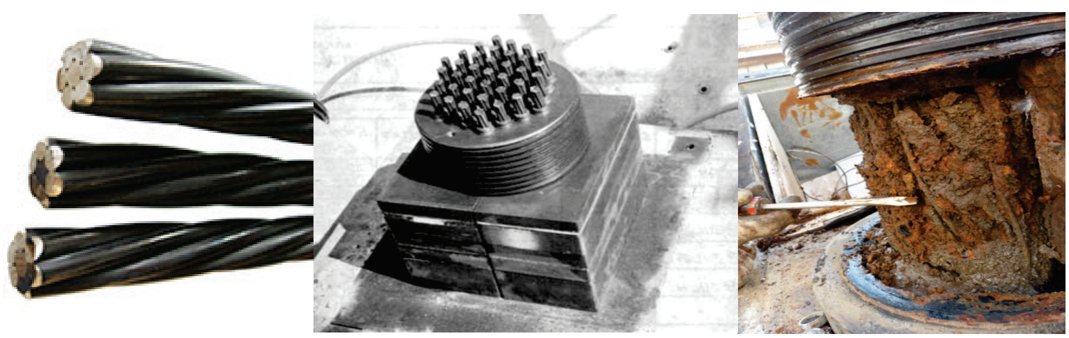

Figure 1. (left) Typical seven-strand cables; (middle) newly installed multistrand anchor head; (right) area under anchor head filled with corrosion product after 30 years of moisture intrusion.

The primary deterioration mechanism is pitting-corrosion-based loss of cable cross section, generally near the anchor heads and most commonly due to moisture intrusion into the post-tension system. Critical area and radius corrosion loss to cables often results in single wire failures, which

may or may not visibly eject wires from the exposed grip wedge. Figure 1 (right) shows a heavily corroded anchorage that was examined during this project. In dams, generally only one end of the cable is accessible. Additionally with navigation structures, the cable's path is most often deep within the concrete, and inspection methods that rely on shallow concrete cover are not applicable. These characterization technologies that are not generally applicable to locks and dams include magnetic polarity scans, corrosion potential/current measurements, impulse response of the structure, ground penetrating radar, and any form of probing or excavation. Also, in large concrete masses, there is generally less known about the cables' local environment. Literature reviews conducted in this project have confirmed that a new method must be developed if improved condition assessment of in situ post-tension cables in navigational structures is to be achieved.

**INITIAL GUIDED WAVE INVESTIGATIONS:** In the 2012 Federal Highway Works Administration report (Azizinamini and Gull 2012) on candidate inspection technologies for post-tensioned bridges, guided waves were called out as a promising area needing further research. When one applies the inspection limitations typical for dams, access to only one end and typically no shallow concrete cover sections, then guided waves and acoustic emission are two of the more favorable inspection options. Acoustic emission is expensive and requires a constantly maintained monitoring system to be in place. For the case of embedded cables, this is covered in a 2009 California Department of Transportation report (Bartoli et al. 2009). Due to system expense and complexity, it was removed from the NDT approach of this project.

Much of the published guided wave research that has been conducted on seven-strand cables deals with the unembedded case or the lower-order modes, which in general do not propagate through the gripping wedge. In initial lower-order guided wave testing with nonembedded cables and lower-order modes, echo reflection was easily achievable at 210 ft of propagation. The addition of cable tension and embedding media (such as grease or grout) severely attenuates lower-order mode guided waves. While these lower-order modes have increased sensitivity to small surface defects, they lack the ability to travel far through the gripping wedge and the surrounding embedding media due to their higher surface mobility. Research also shows that the lower-order modes are tightly packed (i.e., have high spectral overlap) and change significantly under tension, which is additionally problematic when sending and receiving from the untensioned (exposed) end of cables. In the "Standing Wave Based Broken Wire Detection" section of this report, lower frequencies associated with forced vibration modes are examined as a tool for short-distance detection of broken wires. Detection of broken wires is both a needed tool for inspection and a step in the direction of ultimately desired cross-sectional loss assessment. The section of this report titled "DETECTION OF BROKEN WIRES" will address the application of higher-order guided waves for broken strand detection in tensioned and embedded cables and will present recent findings from that research.

**Higher-Order Guided Waves.** Higher-order, longitudinal-mode guided waves experience relatively lower attenuation rates in the embedded case than the lower-order modes. This observation, which agrees with published literature, was first made in trunnion anchor rod research and then in post-tension cable investigations. The low-loss, higher-order modes and their attenuation rates are a function of the inspected elements' diameter and material properties. Because material attenuation increases with frequency due to material-based grain scattering, these higher-order modes experience upper frequency limit. The two frequency plots in Figure 2 show spectral representations of lower-loss guided wave modes for both a solid rod of 1.3 in. nominal

diameter and the seven-strand cable where the strands are approximately .2 in. in diameter, and the entire cable is .6 in. in diameter. Additional discussions of higher-order guided wave propagation in solid rods are provided in Evans and Haskins (2015).

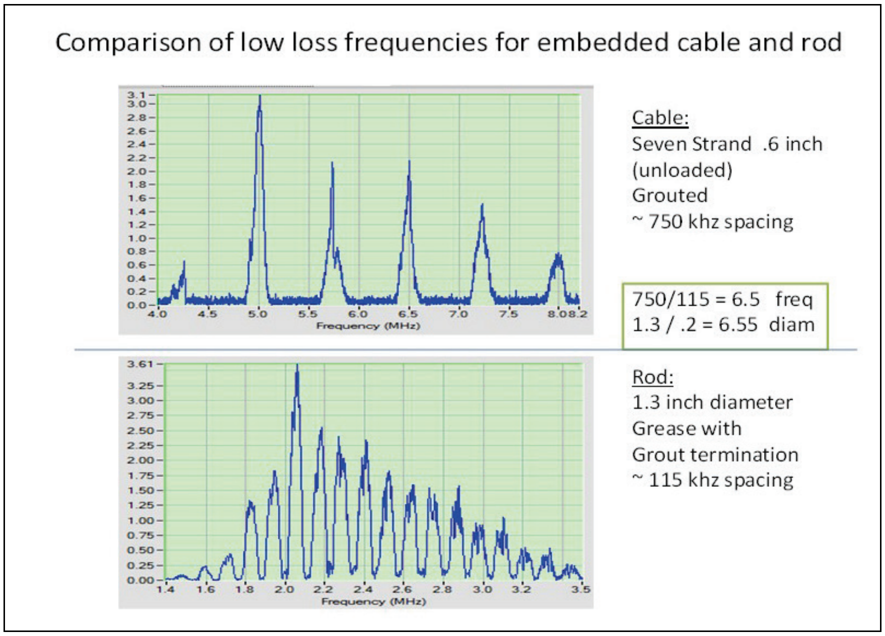


Figure 2. Higher-order, low-loss guided waves in post-tension cable (top) and rod (bottom).

The spectral representations in Figure 2 do not show the influence of the group velocity. Group velocity is the speed of the information packet, which in general over this range is increasing with frequency. Using a short-distance, through-transmission, broad-band impact, this can be visualized for the tensioned and embedded case. Figure 3 shows a gated energy scan (top) compared with a broad band mechanical impact (bottom). The vertical axis on the bottom figure illustrates the group velocity effect where the various modes have changing propagation velocities associated with them.

In the guided wave spectral responses shown in Figures 2 and 3, the entire cable is coupled to the ultrasonic transducer. Experiments were also conducted using a very small diameter (.2 in.) transducer coupled to either the center *king* wire, which is straight and very slightly larger (5 %), and to the perimeter wires, which are helically twisted around the center wire. Figure 4 shows the difference in propagating mode frequencies between the perimeter wire and center wire. In general, propagating energy prefers the king wire even though there are six perimeter wires. This is likely due in part to the facts that the perimeter wires are typically cut at an angle to their primary axis and also that these wires have significant surface contact with the embedding media. The angular cuts in the perimeter wire, which are an orthogonal cut of the entire cable, produce high loss levels of the reflected and transmitted propagating guided waves as described in Beard (2003).

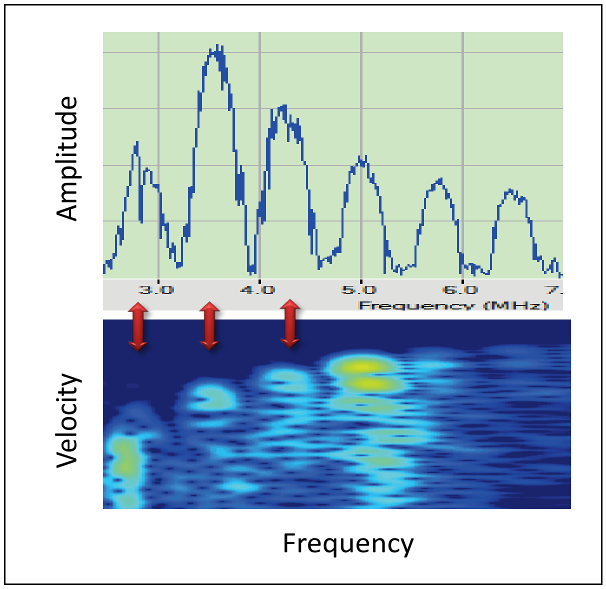


Figure 3. Group velocity of higher-order, low-loss modes.

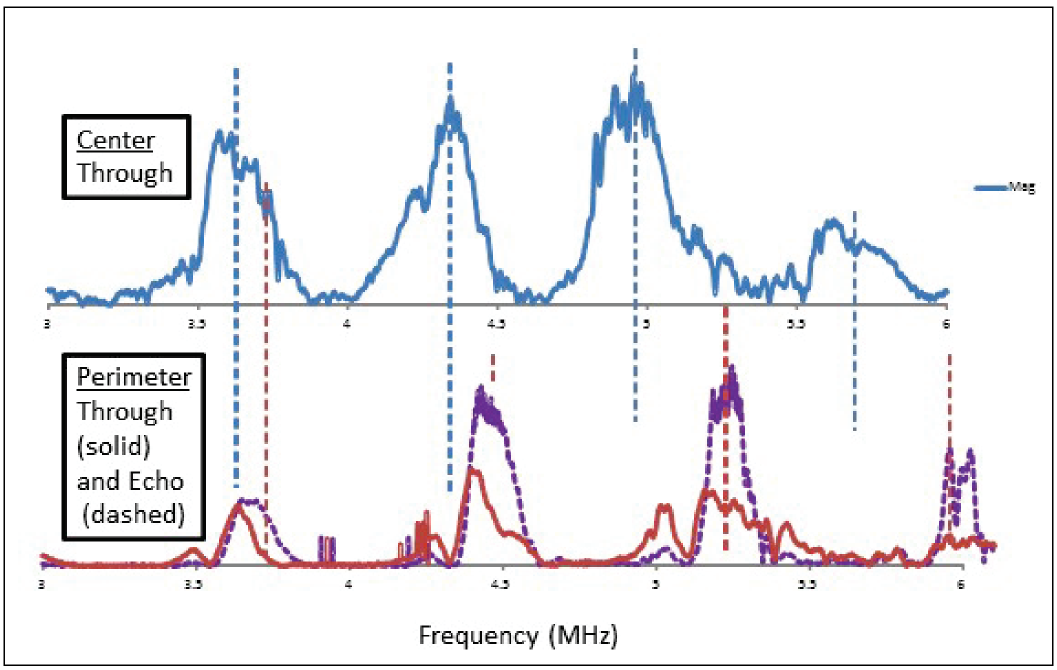


Figure 4. Guided wave frequencies propagating on the center king wire (top) and perimeter wires (bottom).

**Torsional Guided Wave.** Experiments also indicate the presence of a propagating torsional mode approximately 1.4 Mhz. This mode is identified as torsional because it does not appear to undergo dispersion as it propagates. While this mode has been identified in a large number of tests, it does not appear to be as robust in terms of its sensitivity to transducer coupling. Torsional modes ranges have been limited to distances less than 15 ft of propagation. Figure 5 shows two visualizations of the 1.4 Mhz mode.

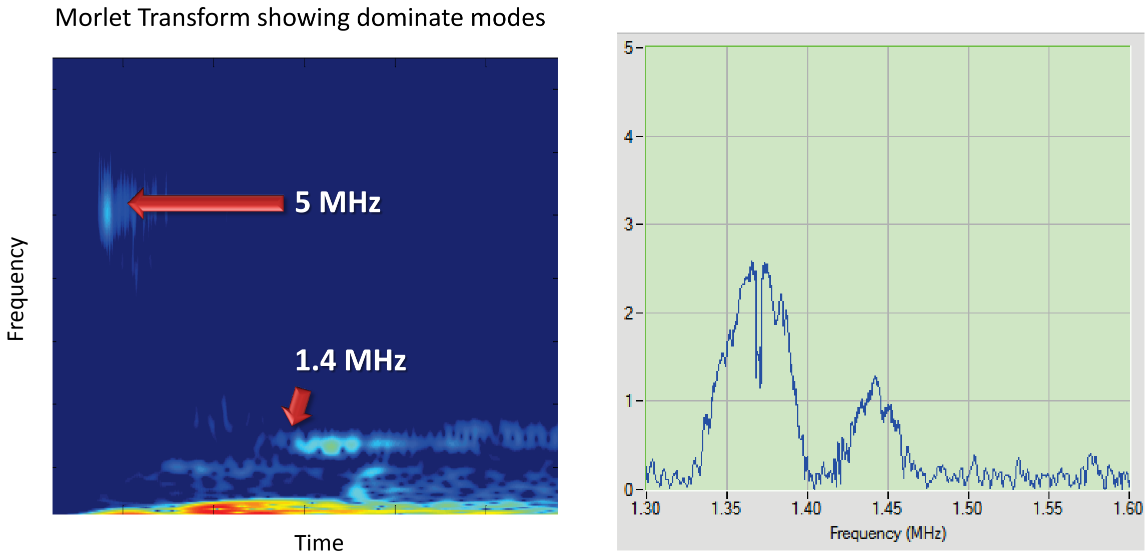


Figure 5. Two visualizations of the 1.4 Mhz mode, which is thought to be a torsional mode. The cable is tensioned to 27,000 lb and embedded in grease.

**Time Domain Utilization.** While the frequency domain provides the primary tool to identify the ideal propagating modes, the inspection itself is typically carried out in the time domain. The selected tone-burst frequency is transmitted with a high cycle count to produce a narrowband signal whose bandwidth does not leak into adjacent modes. One limiting aspect for practical cable application has been that propagation distances have not yet been achievable that match typical in situ cable lengths. In the laboratory, cable inspection or reverberation lengths have been limited to approximately 15 to 20 ft (depending on the tension level and embedment conditions). In Figure 6, reverberant time domain echoes are shown from a 2 ft section of grout-embedded cable. The addition of a time-corrected gain circuit improves the system's dynamic range (top trace in Figure 6) and allows clear resolution of both the first and fourth reflection. The last echo represents 16 total ft of propagation in the embedded post-tensioned cable. The bottom blue trace in Figure 6 is the time-based gain function that was applied to the middle trace.

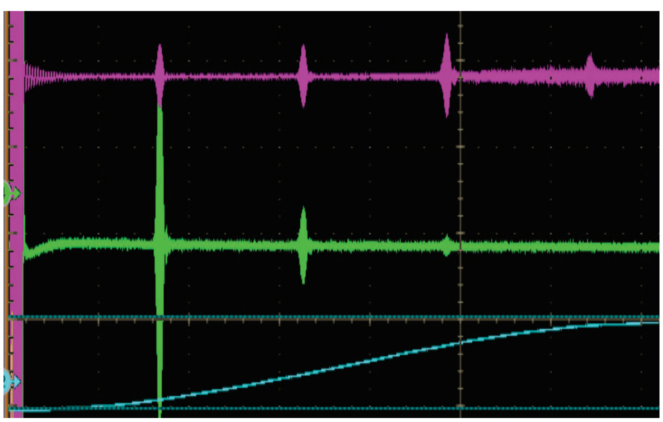

Figure 6. Time domain signal showing end of cable reflections from a 2 ft section of embedded cable.

**DETECTION OF BROKEN WIRES:** When control cases of embedded and tensioned shallow-notched perimeter wires were tested with the low-loss, higher-order guided waves, they failed to show clear echoes from the defects. These same defects had previously been observed as echoes for the case of nonembedded cables. In an effort to simplify the detection problem, cables that had an entire cut perimeter wire were tensioned and embedded. The typical transmission of higher-order modes still failed to clearly detect these broken wires. Additional experimentation with this control set found a unique set of very narrow band frequencies that did clearly show the presence of the cut strands.

**Detection Using Notch Frequencies.** It should be noted here that *notch* frequency is not referring to the lower-order mode notch frequency for cable inspection that is described in the literature as being a tension indicator. That frequency is an absence of energy that is inversely and logarithmically proportional to tension in nonembedded cables (disappearance of all modes typically around 75 KHz). Despite literature searches and several email discussions with Dr. Lowe[1], who described the presence of this notch phenomena in higher-order modes (Beard 2003), very little insight has been gained regarding the cause of the effect. The authors believe it to be related to some form of destructive wave interference. To detect these notches, a high-resolution frequency scan has to be performed; otherwise, the point is jumped over and does not appear in the resulting spectrum. Beard (2003) described these as a point of low propagation occurring near the center of a low-loss mode. These spectral points are consistently observable in higher-order guided wave scans of both rods and cables.

<u>Defect indication was found to be optimal in the descending slope of these notch frequencies</u> and was consistent regardless on which low-loss mode they occurred. This finding was achieved by monitoring the time signals in the vicinity of where an echo was expected as the inspection frequency was incremented on a fine scale. Figure 7 shows the occurrence of a higher-order, low-loss notch frequency.

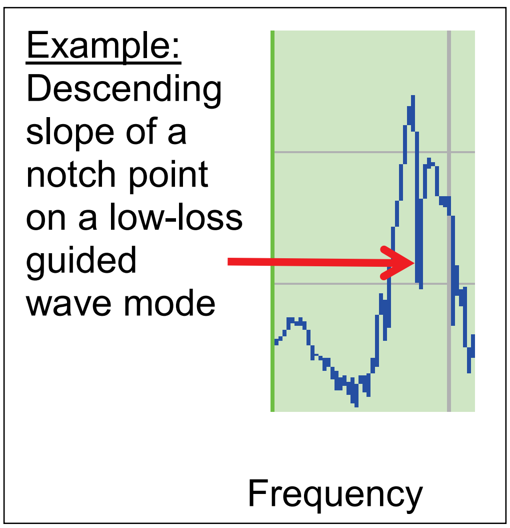


Figure 7. Optimal inspection frequency for defect detection occurring near a higher-order mode notch.

[1]Dr. M. J. S. Lowe, Imperial College London, personal communication with Haskins and Evans, fall 2014 – spring 2015.

In Figure 8, three time signals show the broken wire being detected across three notch frequencies that correspond to three separate low-loss higher-order modes. These defects were also detected at their proper locations when the transducer was moved to the other end of the cable. This corresponded to detection of cut wire locations corresponding to one-third and two-thirds of the cable length or 16 and 32 in., respectively. The initial energy prior to the detected defect is attributable to the gripping wedge and the transition from nontensioned-to-tensioned cable states. The inspection frequencies are also labeled in their corresponding signals in Figure 8.

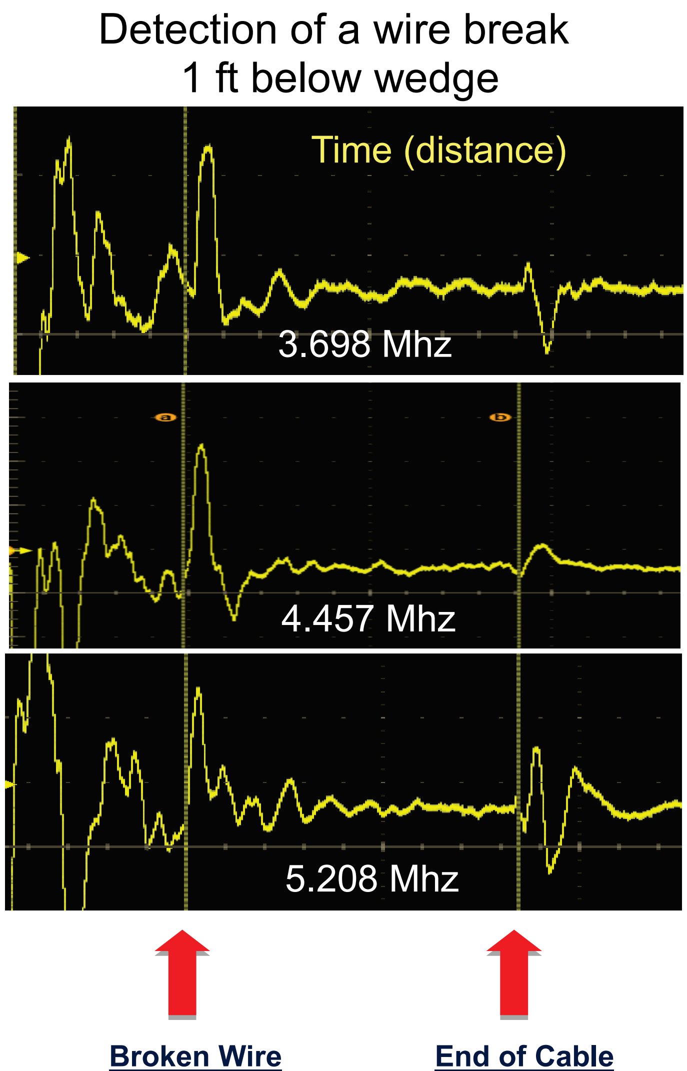


Figure 8. Broken wire detection at 16 in. performed at the higher-order notch frequencies for a tensioned and embedded cable.

While this is an interesting and novel finding, several challenges remain in translating this to a practical field inspection method to detect damaged wires. The primary challenge is that the notch frequency is narrow, and finding it in this case was performed by monitoring the spectrum of the end-of-cable reflection of the relatively short cable section. The degree to which this frequency will change across delivered cables is unknown. Potential methods of acquiring this

notch frequency without a coherent end-of-cable reflection for reference (i.e., most in situ cables are tens to hundreds of feet) has yet to be determined. The potentially interfering reflection from the wedge at the signal start is less of a problem and can likely be addressed by data comparison processes or signal processing operations such as matched filters. This method also needs further investigation to quantify its performance on wires that are missing cross section or in a control case, notched. Unfortunately, the physical manifestation of pitting corrosion especially at high levels is that it does not create an orthogonal defect plane but instead is a sloping defect whose reflective surface is highly varied with respect to incidence angle.

**Standing Wave Based Broken Wire Detection.** Laboratory observation of successful impact propagation through the cut strands on the recovered John Day anchor head specimens led to motivation to further explore high-energy, low-frequency propagation as a means of detecting broken wires in the anchor head region. The thought process is that broken wires forced into vibration should produce spectral components that are attributable to their longitudinal and/or flexural resonances. Figure 9 shows both the resonance of the anchor head itself from direct measure (left pane) and some expected fundamental modes from the cables (right pane) . As vibrational responses are complex, careful excitation/stimulation control and global data comparisons are likely key requirements for successful field utilization. This effort started with highly simplified sample specimens and then with increased complexity to more representative control samples.

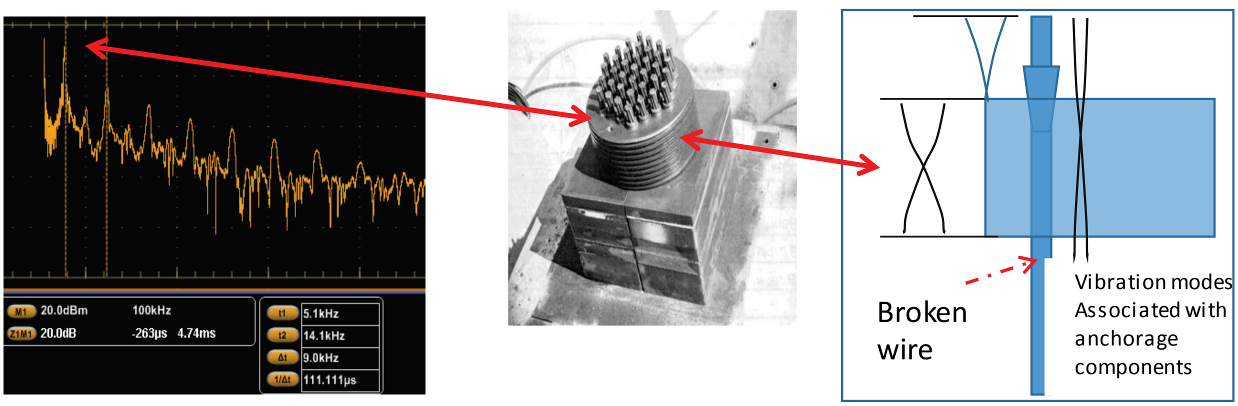


Figure 9. Resonance component of steel anchor head (left); possible vibration modes from testing a cable with a broken strand.

Investigations with highly damped, solid bars found that sustained specimen excitation through long-duration frequency chirps or more controlled phase lock amplifier scans was needed to detect resonance. Simulated damping on rod specimens was accomplished by application of thick coupling grease and clamping to large, structural masses. On cables, damping was introduced by grease, steel hose clamps, heat-shrink, and clamped-on wedges.

Several transmitter and receiver combinations were investigated in through-transmission performance testing. Single-sided stimulation and detection remains an engineering challenge in terms of both designing a transducer/mounting system and in dealing with the increased receiver/transmitter coupling from same-side excitation.

Figure 10 shows undamped cable testing (top) and some of the control specimens (bottom). Six control specimens were created: three solid cables at 1, 2, and 3 ft lengths; three of the same lengths with defects of a cut wire at two-thirds of the cables' lengths. For each cut, the short section of the cut wire was removed from the seven-wire bundle. On the stimulation side, a commercial bone transduction transducer produced good excitation results, though the influence of its own resonance peaks in the 3–5 KHz range do color the overall spectral response. This can be corrected by amplitude compensation in either generation or reception. A laser vibrometer was used to provide broad-band, no-loading, high spatial resolution feedback on cable vibrations. Accelerometers and pvdf-film receivers were used for actual data collection as they represent more practical field transducers.

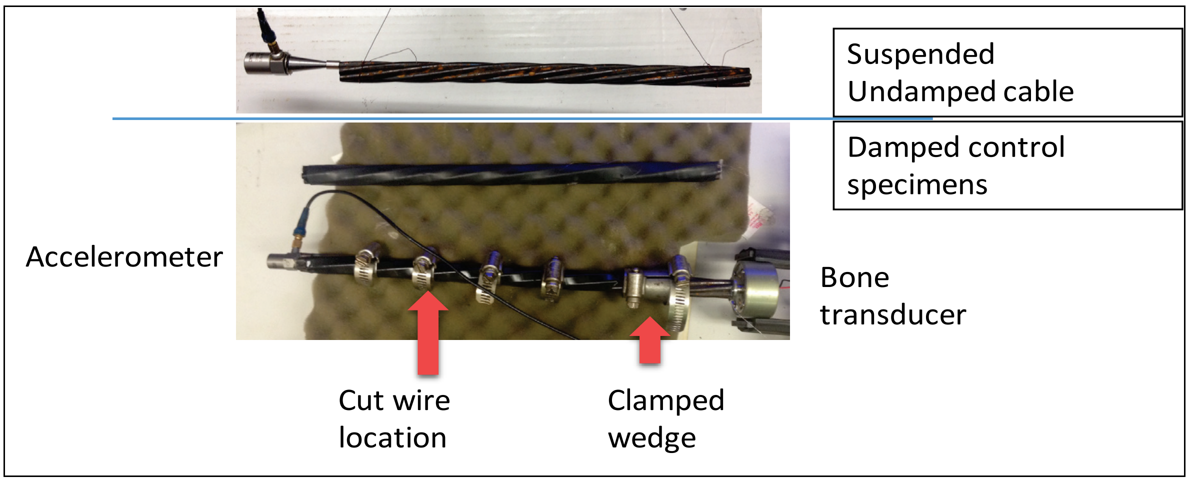


Figure 10. Idealized cable resonance condition (top) and damped specimens with cut wires (bottom).

The spectrum in Figure 11 shows variations in spectral response between an intact specimen (top) and a specimen of the same length and confinement containing a broken wire (bottom). ASTM E1875 Standard Test Method for Dynamic Young's Modulus, Shear Modulus, and Poisson's Ratio by Sonic Resonance, was also studied to gain additional insight into flexural and torsional resonance modes of simple geometries as well as the effects of transducer and node variations. Ideally, this inspection approach would utilize longitudinal mode resonance; however, flexural and torsional modes will most likely appear within the collected datasets.

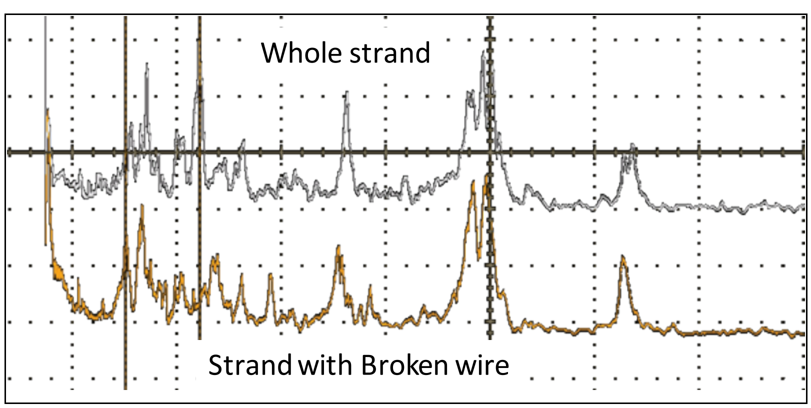


Figure 11. Spectral comparison of whole strand (top) and strand with broken wire (bottom).

**Global Data Analysis of Broken Wires.** The next stage of this effort should be to mock up a multistrand anchor head with embedded and tensioned cables with some having breaks at or near the gripping wedge. The cable test bed could be used for this phase as it has provisions for a five-strand anchorage and grease injection ports. A one-sided transducer capable of injecting forced vibrations along with a proximally located receiver would be needed in the next stage proof of concept. This transducer should have a means of being consistently coupled to the exposed (helical) cable end and of addressing size constraints caused by adjacent cables in the anchor head. Ultimately, spectral comparisons of the collected datasets will be used to detect changes attributable to the broken wires. Retesting may be necessary on locations exhibiting change to verify the anomaly is not coupling related. This sort of relative comparison has been used in methods such as concrete impact echo testing near edges and joints where the spectrums are complex but consistent across similar cross-sectional geometries.

**RESULTS AND CONCLUSIONS:** Broken wires were studied in this research because they represent an easier first-step detection target compared to pitting-corrosion section loss. Also, their occurrence in the field is elusive as breakages do not always result in ejected wires (Ebeling 2013). This report builds on the previous findings regarding higher-order, low-loss modes as a means of defect detection. A narrow frequency band within these low-loss, higher-order modes (just prior to the notch frequency) was found that provided good detection and localization of broken wires. An additional method was also explored that used forced vibrational excitation to create standing wave responses from the broken wires. The proof of concept was accomplished for a two-sided approach on small, damped control samples.

While both approaches have shown success in these controlled laboratory tests, each one faces its own challenges in terms of implementation. For the guided wave approach, the primary challenge is in identifying the notch frequency without a coherent end-of-cable reflection. It is believed at this point that variations in metallurgy from cable batches will be enough to significantly change the inspection frequencies from those specific sets of frequencies identified in this work (Figure 8). For the standing wave approach, a consistently coupled, one-sided transducer is needed in conjunction with the multistrand anchor head physical mock-up to verify the global spectral comparison approach for broken wire detection.

The ultimate goal of nondestructively characterizing cross-sectional loss in corrosion-deteriorated post-tension strands is moved forward by the effort documented here, which has identified promising techniques to detect fully broken strands. The next step would be evaluation of these techniques on control specimens with progressively shallower and less orthogonal cuts or notches. Successful detection of notches at one-third to one-fourth the determined critical diameter would be followed up by evaluation on existing laboratory corroded samples.

**ADDITIONAL INFORMATION:** This CHETN is a product of the Probabilistic Assessment of the Reduced Capacity of Multistrand Post Tensioned Ground Anchorage Due to Tendon Corrosion Work Unit of the Navigation Safety Research Program being conducted at the U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory. Questions about this technical note can be addressed to Dr. Robert Ebeling (601-634-3458; email: *Robert.M.Ebeling@usace.army.mil*). This technical note should be cited as follows:

Haskins, R., J. Evans, and R. Ebeling. 2016. *Development of a new nondestructive inspection strategy for corroded multistrand anchor cables.* ERDC/CHL CHETN-IX-42. Vicksburg, MS: U.S. Army Engineer Research and Development Center. http://chl.erdc.usace.army.mil/chetn

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